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Combining flexible regulatory and economic instruments for agriculture water demand control under climate change in Beauce

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ABSTRACT

Agricultural water management is becoming a critical issue in many parts of the world and cost-effective water policies are required to control water use. We examine the case study of irrigated agriculture in Beauce, France (9750 km^2, Europe's largest cereal producing region). We explore the mechanisms for water abstraction control involving a combination of regulatory and economic instruments. The analysis is conducted with a hydro-economic model that includes a calibrated economic model and a semi-distributed calibrated hydrogeological model. First, we analyse the system currently used to manage groundwater abstraction. It includes a flexible quota system, revised annually as a function of the state of the groundwater, combined with a tax. This dual system performs better than a single instrument because of regional hydrogeological and economic specificities, as well as the fact that it limits costs for farming. We then investigate the impact of alternative combinations of instruments. Our findings show that the most cost-effective and robust way to improve the groundwater state is to increase the economic component (a flexible tax) in association with a flexible quota system.

1. Introduction

With increasing environmental constraints and rising water demands, managing water allocation has become a critical issue in many parts of the world. In the farming sector demand for irrigation is significant and growing [1]. The sector is also affected by greater regulatory and climatic constraints. Related problems include the over-allocation of water for agricultural purposes with respect to resource capacity [2]. In this context, both institutions and individuals are developing coping strategies. Thus, there is clearly a need for instruments that are capable of meeting environmental performance targets and limiting the cost of diminishing water availability. These instruments should take into account adaptation of farmers, as well as variability and uncertainty of water resources (supply capacity and demand). The policy debate about the best combination of instruments is central to the majority of environmental problems and is characterised by the control of negative externalities or the provision of public goods.

Essentially, two types of instruments can be adopted by policy makers. The first type is geared to quantitative control, such as norms or quotas, which limit input use or output emissions. The second type includes price-based or economic instruments, such as taxes on inputs or outputs, as well as subsidies intended to encourage the adoption of good practices and technologies. Economic instruments are expected to affect input use by increasing or decreasing the cost for the producer or consumer. Thus, they provide an incentive in terms of the cost-effective allocation of scarce resources. However, this may fail to change farmer behaviour if the “cost of change” (which is not only monetary) exceeds the benefit of change, because ultimately, the economic and technical choice of adaptation depends on the farmer [3]; Chap. 1). Rey et al. [4] review the implementation of economic instruments throughout

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Europe. A variety of economic instruments can be considered as discussed by Koundouri [5]; for example: trading quotas (markets), revising cap or tax levels, buybacks [6] or combining instruments. Other type of instruments, such as voluntary-based mechanisms also exist.

From a purely theoretical point of view these two main types of instruments are equivalent (Weitzman, 1974). However, information asymmetries, uncertainties about processes (water demand) and rationality are just some of the factors that undermine this equivalency.[1] Economic instruments, such as taxes, also have the so-called *double dividend* advantage: they generate public revenues that can be used to improve water management[2] in addition to incentivising behaviour. However, often they also imply high transaction costs. Although economic and regulatory instruments are often opposed, they can be more effective and cost-effective when used in combination. In this study, we explore how such a combination can cope with variability and uncertainty in terms of water supply and demand. The Tinbergen rule[3] states that each policy objective requires a specific instrument to have an effective policy mix. Young [7] develops this rule for agricultural water management and for the design of efficient administrative settings of water use and allocation. He suggests, among other rules, to "unbundle" policy objectives e.g. to distinguish historic/permanent entitlements and yearly/daily allocations of water.

This paper examines water abstraction control mechanisms and the robustness of original combinations of instruments in Beauce, in a reference scenario and for future scenarios of climate change and price uncertainty. Beauce is located in the "central" region of France. It is the main cereal-producing region in Europe [8]. Farmers irrigate a significant share of the cropping area. Given the sensitivity of the water resource, water policies have been adopted to control withdrawals for more than 20 years in order to avoid drought in connected surface watercourses [9]. A flexible quota is revised annually depending on the groundwater level in four regions in Beauce. Thus, farmers face varying constraints from year to year. This quota is combined with a tax on water abstraction (from the WFD). The quota has been designed locally to safeguard piezometric levels. The tax has not been designed locally, as it has been introduced with the WFD and the french water law. The rationale is both to have farmers contributing financially for their potential harm on the environment and to act as an incentive to save water, as mentioned above with the *double dividend advantage*. The analysis of the control mechanisms for water withdrawal is supported by a theoretical analysis and a calibrated hydro-economic model (HEM) that represents farming behaviour and connected groundwater resources. This original contribution to the literature showcases Beauce's unique control mechanism for groundwater abstraction. It provides an economic analysis and explores the effectiveness and cost-effectiveness of alternative combinations of instruments to increase environmental compliance and limit social cost. Several alternatives are considered: (i) economic instruments, such as flexible taxes that depend on the yearly state of groundwater resources and higher taxes and subsidies to reduce water use (buy-backs and premiums to reduce irrigation); (ii) alternative regulatory measures, such as increased restrictions and spatial disaggregation in terms of piezometric head monitoring and restriction; and (iii) a supply side option, involving groundwater substitution. We also test the robustness of alternative combinations of instruments in relation to their capacity to cope with uncertainty and avoid undesirable outcomes.

A pragmatic approach is required to explore the cost and effect of policies for improving the management of water resources and to analyse the observed water allocation and behaviour. Hydro-economic models are a vast ensemble of models characterised by at least one representation of economic processes (production and/or consumption) and hydro (geo)logical processes (see e.g. Harou et al. [10]. The principle of hydro-economic models is to connect these different compartments. The models represent the real world rules and processes of case studies, which link the parameters within the hydro-economic system under study. The economics and biophysics of water resource dynamics can be considered together when the cost of the resource and the regulation (i.e. water rights or water restrictions) are dependent on the state of water resources and when water uptake (by economic agents) impacts the water resources. It is important to consider specific economic processes, such as farming's adaptation to changing constraints and institutional adaptation to regulate access to water (in response to the impact of climate change or global change) in order to ensure that the resulting economic and hydrologic balances are not distorted. Assessing the impact of climate change on water resources already presents a scientific challenge, even when economic factors are not considered [11,12]. However, the impact may be over- or underestimated, if we fail to account of the increase in crop water requirements that are not satisfied because of regulations or the farming sector's capacity to adapt.[4]

The rest of this paper is organised as follows: after this introduction, the second section presents groundwater management and policies in Beauce; the third explains the background to hydro-economic modelling and robustness; the fourth describes the hydro-economic model; the fifth presents the simulation results of the reference situation and alternative instruments with climate change scenarios.

2. Groundwater management and policies in Beauce, France

2.1. Farming and irrigation in Beauce

Beauce is Europe's main cereal producer. It is one of the most irrigated farming regions in France and covers about 650 000 ha.

[1] Weitzman (1974) discusses this economic issue in detail.

[2] this not the case with a market where the value is captured by private agents.

[3] Tinbergen [44] was awarded the first Nobel Prize in Economics for his work on economic policy. His work dealt with policy arrangements that are dynamically efficient.

[4] e.g Ducharne et al. [45] do not consider these adaptations and might overestimate the increase in withdrawals from farming.

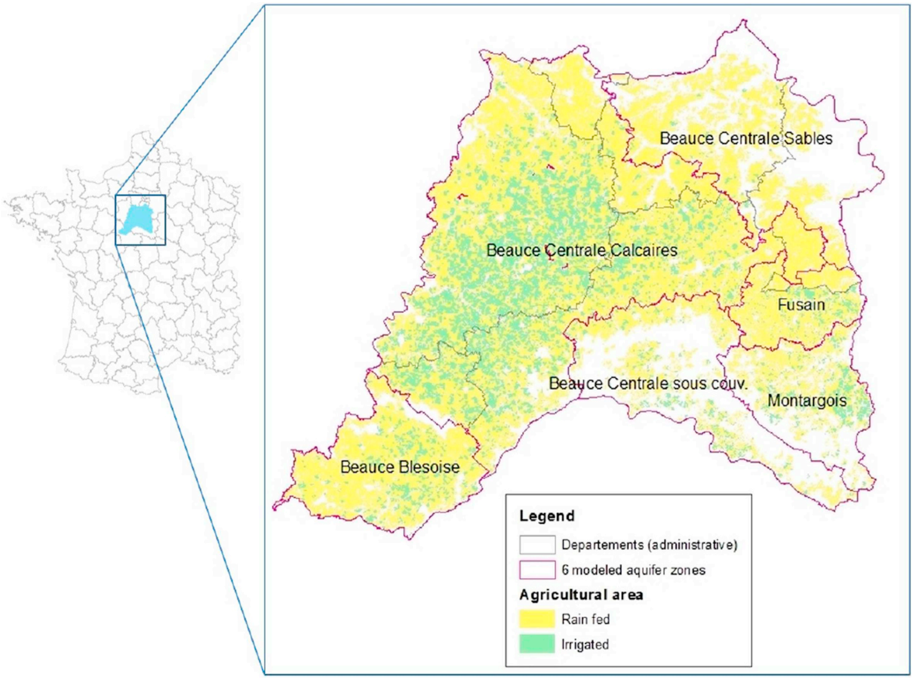

Fig. 1. Zoning adopted in the hydro-economic model.

Fig. 1 shows its location, as well as the irrigated and non-irrigated areas. Since the 1970s, irrigation has developed substantially to cope with dry years, secure high yields and enable the diversification of crop production, particularly crops grown under contract for the agro-food industry. Depending on the year, between 120 000 and 240 000 ha are now irrigated using pivot and hose-reel irrigation systems. Between 150 and 450 million m^3 per year. Farmers have access to the water resource with individual wells.

Irrigation essentially relies on a large groundwater resource, namely, the Beauce aquifer, which is located under the Seine and Loire surface water basins. It is a multi-layered aquifer with sands, chalk and limestone that covers 9.700 km^2. The Beauce aquifer, once called the "château d'eau" (water tower) of France, is used for irrigation, drinking water, and industry: industrial abstrations are around 40 millions m^3 and drinking water uses some 70 millions m^3 per year. It also feeds natural surface-water systems, thereby, providing important ecosystem services (wetlands, biodiversity). This aquifer system is subject to quantitative problems, as evidenced by the lowering of the water table since the beginning of the 1990s and the reduced flows (drought) on connected surface rivers.

2.2. Water policy in Beauce

Since the 1990s, the government has implemented local water policy measures and instruments in consultation with agricultural representatives to deal with surface and groundwater issues relating to drought. In 1994, the volumetric management of withdrawals started with the obligation to install meters at individual wells. In 1997 and 1998, a stakeholder group was set up and a series of studies (including modelling approaches) was launched to support the policy process. The overarching framework is now the French Water Law, which is the translation of the European Water Framework Directive (WFD). The Beauce aquifer has been classified as a "Zone de Répartition des Eaux" (a water distribution zone). This is an important instrument applied by the French Water Law in order to comply with the WFD and ensure that bodies of water achieve a good status. This classification states that all withdrawals must be submitted for prior governmental authorisation. The perimeter of the local water management plan (SAGE[5]) was determined in 1999 and adopted in consultation with stakeholders in 2013. The objectives of the SAGE are to determine the principles, means and goals required to reach a balance for water use, which guarantees water security for all and safeguards or restores the good state of natural ecosystems. Since 2017, the control of water withdrawals has been delegated to a "single collective management body", which ensures that the total volume of water withdrawal does not exceed the yearly authorisation level. This replaces the system where farmers were individually required to declare (and respect) their volumes to the authorities. The question of the global quota allocation is central to this new governance framework.

In Beauce, two types of water policy instruments are used in quantitative water management: (i) planning instruments, which aim to balance uses with the capacity of the resource to avoid crisis management (details are given in the following paragraph); and (ii) crisis instruments, which aim to limit the impact of a drought (surface river flow below threshold levels). Details of crisis

[5] In France, the SAGE "Schema d'amenagement de gestion des eaux" (Water Management Plan) is the local, basin scale governance instrument developed in territories with water management problems.

management in Beauce are provided in Appendix 1. While this issue is beyond the scope of this paper, it is interesting to complement our understanding of Beauce's water governance.

2.2.1. Water demand control and planning in Beauce

The existing planning policy is a combination of regulatory and economic instruments. The regulatory instrument is a flexible quota and the economic instrument is a water tax. A technical measure was also implemented, involving the removal of a series of wells,[6] because pumping in wells located near the stream directly affected the flow rate of a few small and highly sensitive water-courses. The following two paragraphs provide details of the flexible quota and the water tax.

In 1997, a volume-based quota system was introduced. Each year, a coefficient reflecting the state of the groundwater at the beginning of the cropping season is defined by the administration. The quota is updated every year at the beginning of the season, by multiplying the reference quota by the yearly coefficient to determine the volume that can be withdrawn each year. Since 2009, individual coefficients have also been calculated for four hydrogeological units (sub-sectors of the Beauce aquifer) that display differing hydrodynamic properties. The reference quota, i.e. when coefficients are 1, is 420 million m^3.

Two thresholds (H1 and H2) determine the coefficient (Appendix 4 shows the yearly coefficient according to the piezometric level for the Beauce Centrale region). H3 is the highest "alert" threshold. So far, the values for the coefficient vary between 0.4 and 1, depending on the year and the region. The government publishes the yearly water availability coefficient around the 1The government publishes the yearly water of April. During the year, a website informs farmers about changes in groundwater levels, which means they can anticipate the level of the coefficient before the official statement is released. Another characteristic of the quota system is that there are no restrictions on the dynamics of water use, in other words water may be used partially or totally on spring or summer crops. Thus, farmers must plan cropping and irrigation patterns jointly at the beginning of the growing season, despite the uncertainty regarding spring and summer weather conditions.

To comply with the WFD "water pays water" principle, a water tax is collected in France from all farmers that abstract more than 1000 m^3. The amount is fixed in relation to the basin and the user type. The reference tax level is $tax_{ref} = 0.014€/m^3$ for farmers in Beauce. Although the effect of this instrument will be analysed in this paper, one should keep in mind that it has not been locally adapted to act on behaviour as an incentive. The tax is designed in its principles at national level with a policy objective of preventing or reparing damages caused to the environment by collecting public revenue and acting as an incentive for water use to avoid misuse. The amount can be adapted if the water body is in a" Zone de Répartition des Eaux" i.e. if the water body is with quantitative problems, but it has not been (and is never to the extend of our knowledge) adapted to local economic conditions to ensure it acts as an incentive.[7]

2.2.2. Analysis of the interest of the actual instruments in Beauce

The originality of the Beauce quota system is that it varies depending on the state of the groundwater. This is useful because it significantly reduces the cost for farming compared to a fixed quota system. A fixed quota (based on dry years) would limit water use above the necessary level and induce significant costs in relatively wet years. A fixed quota (based on average or wet years) would not provide the same environmental benefits and would not comply with the WFD.

The flexible quota and the tax on water withdrawals are both active instruments that must be respected. However, only one of the two actually restricts the water demand in a given situation. Depending on the circumstances, either the quota system or the tax may determine farmer's behaviour and affect total water demand. This is illustrated in Fig. 2, which shows water demand curves and the variability of the quota constraint for two different situations: (i) the first corresponds to a case, where the quota is a limiting factor and the shadow value of water (λ_{water}) is positive; (ii) in the second case, the tax and total cost of water are limiting factors, the shadow value of water is 0 and the quota does not limit behaviour. In Beauce, both situations occur. They can be observed in different regions within the same year. In the case of a specific region, their occurrence depends on the year and the water demand parameters: input and output prices, as well as the biophysical parameters of water production. Therefore, the variability depends on: (i) water demand and (ii) quota level. Consequently, given the regional hydrogeological and economic characteristics, the use of both instruments improves environmental performance more than in the case with a single instrument. It is also worth mentioning that even when the tax is not constraining water use (and quota is), which is often the case in Beauce, the revenue collected by the government is allocated to implement other water management measures.

The quota system relies on individual historical quotas, the sum of which should correspond to the total volume of water that can be abstracted per year in a given situation (based on a reference or normal situation). However, this is not the case because so-called "dead volumes", corresponding to a share of the volumes of some quotas, are never authorised. This is a problem of over-allocation. The flexible quota system makes it possible to impose a reduction coefficient every year and, thus, manage over-allocation. However, individual discrepancies cannot be managed with this instrument. Indeed, this would require resetting initial entitlements to align them with the total sustainable abstraction volume and not historical practices.

2.2.3. Developing innovative instruments

Although the current management scheme has been recognised as a step towards sustainable management, it has failed to

[6] New wells have been constructed to replace the old ones.

[7] See https://programme-eau-climat.eau-seine-normandie.fr/les-redevances-taux-et-modes-de-calcul and https://aides-redevances.eau-loire-bretagne.fr/home/redevances/agriculture.html.

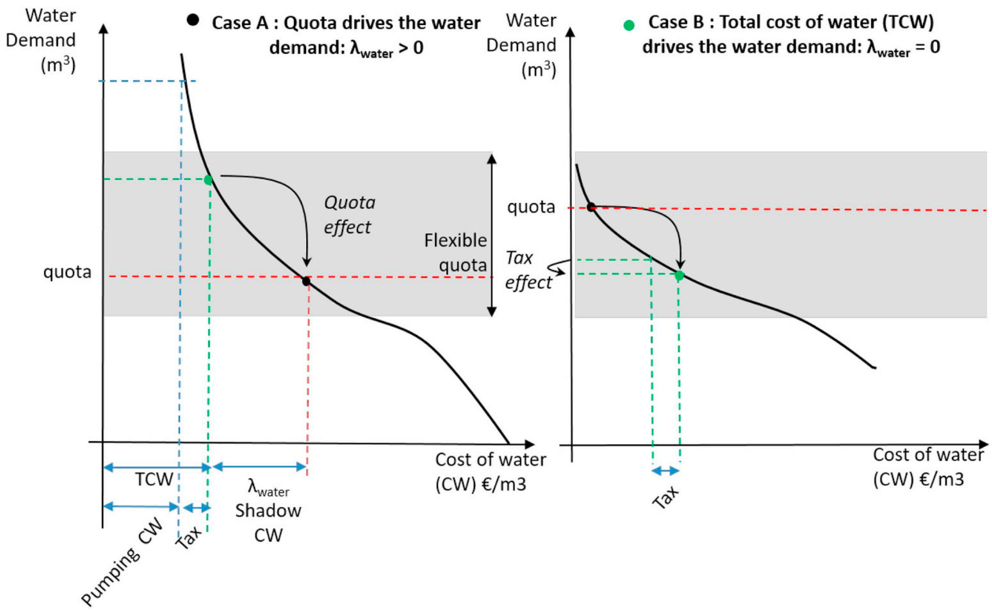

Fig. 2. Schematic illustrations of the quota and tax effects with water demand curves in two different cases: A: quota is driving the demand, $\lambda_{water} > 0$, case B: cost of water (incl. Tax) is driving the demand, $\lambda_{water} = 0$. TCW: total cost of water.

overcome drought-related problems during the summer (alert levels are reached for surface water). This might be accentuated by climate change, as suggested by our modelling results (see Results section). We developed and tested alternative instruments to examine effectiveness and cost-effectiveness for climate change scenarios. They are described below. An overview of the combination of instruments is given in Table 1.

- Baseline with 6 different regions (*6 reg* & *6 reg +*)

On the basis of the zoning of the hydrogeological model (which relies on hydrodynamic properties), we tested the baseline scenario by dividing the Beauce Centrale into three sub-areas to see whether deciphering the coefficient and corresponding water withdrawal rights would improve the level of piezometric heads and at what cost for farmers. The advantage of breaking down the spatial policy level is to get closer to a tailored or first best policy.

After a preliminary evaluation, the instrument seemed unsatisfactory in terms of environmental performance. We then introduced an alternative option for the instrument (*6 reg +*), by reinforcing the quota calculation function. This involved associating a new coefficient to threshold levels (0.2 and 0.05, to S2 and S3, respectively) (Appendix 4 gives the relation between coefficient and piezometric level).

- Water fee based on the piezometric level (*FlxTax*)

To increase the environmental efficiency of the tax mechanism, we indexed the tax rate to the piezometric level. The aim is to

Table 1
Description of innovative irrigation water use planning policies as a combination of demand (regulatory and economic instrument) and supply management. Tax_{ref} = 0.014 €/m^3. GW: Groundwater.

Policies	Demand management instruments		Supply options
	Regulatory inst.	Economic inst.	
Ref	Flex. quota	Tax_{ref}	GW only
6 reg	Flex. quota& 6 reg.	”	”
6 reg+	−20% flex. quota & 6 reg.	”	”
Tax	Fix Quota Coef = 1	”	”
FlxTax	”	Flexible tax indexed on H	”
FlxTxQ	Flexible quota	”	”
Substi	Flexible quota	Tax_{ref}	GW + Pond water
Buybck	Flexible quota	red. of use prem./m^3 & Tax_{ref}	GW only
Desirr	Flexible quota	stop of irrig. prem./ha & Tax_{ref}	GW only

indicate the relative scarcity of the resource through a price signal to reduce water demand in critical years. The tax is calculated as follows $tax_{flx} = 2^{*}tax_{ref}^{*}(1 + h_{highRef} - \tilde{h}_n)$, with $\widetilde{h_n} = \frac{h_n + h_{n-1} + h_{n-2}}{3}$. This means that the current tax rate would be doubled and multiplied by the difference between a mean observed piezometric level and a high water reference piezometer level (2001 is taken as a *high water* reference). If the water level is x meter below the reference level, the tax would be increased of respectively $x * 100\%$. This tax can be charaterized as an ambiant tax [13] given that the same tax is levied on all farmers in the same aquifer area, regardless of their individual water use. The tax is combined with a fixed quota system (coefficient = 1), which is less restrictive than the reference.

- Water tax based on the piezometric level combined with the quota system (*FlxTxQ*)

This instrument combines the previous flexible tax system (*FlxTax*) and the reference flexible quota system.

- Groundwater resource substitution (*Substi*)

One option discussed by the administration is to develop substitute water resources to compensate for the reduction in groundwater availability in the eastern part of the region (Montargois and Fusain). The substitute water resource would be derived from water collected from the farm drainage system and additional surface water is pumped into artificial ponds in the wet season. This solution has a further benefit because it limits the nitrate contamination of water: drainage water is collected in reservoirs and reused for irrigation instead of flowing into the ecosystem. This does not negatively affect the infiltration in the aquifer because the pond recharge occurs in the wet season, when the groundwater flows into surface river systems. The investment costs are estimated to be around 5 €/m^3. With a 30-year depreciation period and a discount rate of 2.5%, the cost amounts to 0.24 €/m^3.

- Quota buybacks (*Buybck*)

Similarly to the premium to reduce irrigation, the idea of buy-back is to pay farmers for all the cubic metres they give up compared to a reference situation (ideally without buy-backs) in return for a uniform payment. In France, this system does not exist, as far as we know. However, it has been applied in Spain [14]. It is a more effective policy than the premium to reduce irrigation. The latter does not take into account water application rates per hectare, which are a determining factor when it comes to reducing irrigation. The farmer may choose to sell their water “right”, by comparing the subsidy payment and the estimated marginal value of water. A buy-back scheme is effective if the level of payment equals the shadow value of water. In our experiment, the buy-back premium was set at 0,20 €/m^3 for the experiment. This incentive should affect the intensive margin adjustment and bring about a shift from highly irrigated crops to less irrigated crops.

- Desirrigation premium (*Desirri*)

Paying farmers to abandon irrigation is already envisaged in France through the “desirrigation” premium as part of the agro-environmental measures (CAP[8] Pillar II). The premium was fixed to 250 €/ha and is payed to farmers, who prove that they have reduced their irrigated area compared to a reference situation. This incentive should affect the extensive margin, bringing about a shift from irrigated areas to non-irrigated areas.

3. Hydro-economic model and robustness analysis

3.1. Current approaches in hydro-economic modelling

The growing concern about the need to coordinate economic and environmental policies calls for a global understanding of the interaction between socio-economics and the biophysical functionning of water resources and related ecosystems. Hydro-economic modelling is a pragmatic response to the need to represent the biophysical and economic system as a whole. The aim of developing this type of model is to understand the impact of climate change (or other global change scenarios) and to simulate alternative management schemes in areas where there is conflict over water or when water causes damage, such as floods [15]. Hydro-economic models are often developed at the scale of water resources to account for local economic, institutional and biophysical characteristics. However, some HEM exist at larger global scales, such as Alcamo, Floerke, and Maerker [16]. Hydro-economic models have developed over the last 10–20 years. Examples can be found all over the world, as quoted by Varela-Ortega et al. [17]. Several authors have reviewed empirical hydro-economic models Harou et al. [10]; Brouwer and Hofkes [18].

The first type can be qualified as analytical models. Typically, they are non-calibrated and adopt a social planner perspective. They are rarely defined as *hydro-economic models* (sometimes they are called *dynamic* or *optimal control* models). Here the central question is the optimal control of temporal groundwater allocation of water from a social point of view, even if this optimum is far from the private optimum that might be closer to the real observed allocation (which might be closer to the genuine allocation observed). Some examples are provided by Burt [19]; Rubio and Casino [20]; Koundouri [21]; Koundouri and Christou [22].

[8] the european Common Agricultural Policy.

A second type includes models with a more empirical approach to hydro-economic modelling. They are designed to represent real world processes without considering whether long-term water use is optimal from a social planners' perspective. This is the approach used in the present study. These models can be used to test: the effect of agricultural water pricing [23], the selection of climate change adaptation measures [24] or to calculate the economic value of water or the costs of water scarcity [25].

Another distinction can be made between models that are spatially explicit (e.g. farm scale/grid model covering several km) and those that model regions (semi-distributed models). The first requires important computational means because data flow has to be managed between different models through coupling (e.g. Bulatewicz et al. [26]; Mulligan et al. [27]). However, they provide spatially explicit information that can be useful to analyse policies and distributional effects on both resources and economics. Good quality economic or hydrological data is rarely available at a spatially explicit level. Alternatively, in the case of regional modelling, good quality data is usually available (standard or historical databases), but at a reduced spatially explicit level. In addition, regional modelling allows for the development of holistic models, which integrate both the economic and hydrological representations of processes on the same platform. This is helpful for supporting large simulation sets to explore uncertainties, such as those related to climate change.

3.2. Robust decision making (RDM)

RDM is an analytical framework that takes account of the profound uncertainties affecting decision-making [28]. It was initially developed by the RAND Corporation to focus on the question of long-term planning and sustainability. It relies on an iterative framework, which connects decision makers with a modelling capacity capable of simulating the effect of uncertainty on performance indicators. Unlike research for optimality, it internalises the uncertainty of some unknown parameters in the selection criteria. This is a different approach to classical optimality criteria, which produces a single outcome for a defined set of input parameters. These approaches are useful for identifying decisions that hedge against uncertainty. Lempert et al. [29] and Hallegatte [30] are central references that develop the RDM analytical framework. The optimality approach explores uncertainty effects with a sensitivity analysis and, thus, may provide different results in relation to the central problem. It differs from RDM criteria, which provide a single outcome for several uncertainty scenarios.

With RDM, a RDM algorithm has to be described to express the selection criteria. Indicators must be calculated for individual results [scenario X instrument] to facilitate the interpretation of a matrix of results. This differs from a "one dimensional" comparison used in a deterministic approach, which is easy to interpret (selection of the option that yields the maximum or minimum, as a function of the selection criteria). The matrix becomes multi-dimensional if several criteria are considered (multiple criteria). The challenge for RDM is to combine the information provided by multiple scenarios of uncertainty for each of the programmes. Indeed, the results (ranking of instruments from the best to the worst according to a given indicator) may vary depending on the scenario. As we have seen previously, a robust instrument is one that avoids critical cases and secures minimum satisfaction in all cases. Several robust decision-making criteria could be envisaged. The Minimum Maximum Regret is a good candidate as it minimises the risk of significant regret and is in line with the concept of robustness. Other criteria, such as the MinMax (selection of the best worst case option, which is more conservative) could have been considered. The advantage of the MinMaxRegret criteria is that they do not require any extra information and can be considered as a starting point in robustness analysis [31]. The regret is the distance between the indicator for an instrument and the best indicator in a given scenario, i.e. there are as many regrets as there are scenarios x instruments. For each instrument, the maximum regret can be calculated for all scenarios. The instrument that provides the minimum maximum regret for all scenarios is chosen with these criteria. Thus, the options can be ranked from least robust to most robust.

4. The Beauce hydro-economic model

We develop a hydro-economic model of agriculture and groundwater in Beauce. It is composed of six independent regional models. The main advantage, which justifies the choice of a holistic hydro-economic model (instead of a compartment model), is that it facilitates the exchange of input and output parameters between models. In our case, this means we can conduct a multiple year simulation, as well as numerous policy or scenario simulations. Three main dynamic connections between the economic and hydrogeological models are represented in our model: (i) irrigation water withdrawal influences the piezometric head of the aquifer, (ii) the yearly regulatory withdrawal constraints depend on the piezometric head level, (iii) the cost of water for farmers is a function of the depth of the aquifer. The latter can be considered a partially internalized externality: the more water farmers pump, the deeper the piezometer level and the higher the cost of supplying water.

The model has a yearly time scale. A hydrological year starts on the 1st of April of each year. This is assumed to be the date when piezometric levels are observed in order to determine the yearly coefficient.[9] The sustainability of the hydrogeological system is ensured when the hydrogeological balance keeps the piezometric levels above a specific threshold.

We build a dynamic recursive model: the optimization of the economic maximisation function is conducted on a yearly basis (n), but it includes constraints based on the piezometric head level in year $n - 1$. It corresponds to a multi-period simulation without inter-temporal optimization.[10]

[9] In reality this date is variable, but it is always in March or April.

[10] Inter-temporal optimization is a multi-time period optimization. This can be useful for two main settings: the first is the farmers' decision with regard to growing perennial crops, e.g. Balali et al. [23]; Connor et al. [46]; the second is the social planner's perspective, which maximises over a long time period. Here, we assume that farmers are *myopic* and do not account for the input allocation in years to come because they grow annual field crops.

In the simulation, the yearly withdrawal coefficients are first calculated according to the piecewise linear functions determined for the region, which give the coefficient as a function of the piezometric level h_n (see Appendix 4). Then, the economic model represents farmers' behaviour in terms of choice of cropping patterns and water allocation at the beginning of the agricultural season in relation to the yearly water availability. It is important to note that some crops have to be sown before the farmers know exactly what the yearly coefficient will be. On the basis of expert advice, we assume that the cropping pattern will not be changed (re-optimised) after the 1st of April.[11] Then, the weather conditions that occur in late spring and summer are randomly and independently drawn from past records and classified as dry, medium and wet. These determine the aquifer recharge, the real water application on crops and the resulting withdrawals. We assume that there is no difference between the abstracted volume and applied volume of water because of individual access and equipment. The hydrogeological model simulates the piezometric head level (h_{n+1}) for the following year $n + 1$ and natural drainage.

4.1. The economic model

The economic model represents the farming sector's behaviour in terms of yearly cropping and input - land and water - allocation at regional level (six regions are considered).[12]

It is a programming model of agricultural supply based on the principles of positive mathematical programming (PMP) [32] with decreasing marginal yields at the crop level and constant elasticity of substitution (CES) between land and water for irrigated crops as refined by Mérel, Simon, and Yi [33]. It is calibrated in order to perfectly replicate the observed reference and the accounting profits. The model is taken from Graveline and Mérel [34].[13] Our economic model has the advantage of representing three potential adaptation margins of farming as broken down by Mérel et al. [35] and described in Graveline and Mérel [34]. These are the super-extensive margin, the extensive and the intensive which are respectively: the shift from irrigated crop to rain-fed crop, the shift from an intensive to a less water intensive crop and the reduction of the applied water quantity for a given crop and land unit.

Agronomic data from Morardet and Hanot [36] on yield response to water is used to calibrate the model (see Graveline and Mérel [34] for more information on the calibration of the yield response elasticity). In the short term, intensive adjustments, often called deficit irrigation,[14] are very likely to occur because they do not involve structural change. They are simply an adaptation of the input application level.

The reference allocation we replicate is a vector ($\bar{q}_i$, $\bar{x}_{i,l}$, $\bar{x}_{i,w}$, $\bar{\eta}_i$, $\bar{y}_{iw}$, $\overline{\lambda_l}$, $\overline{\lambda_w}$) of activity outputs ($\bar{q}_i$), acreages ($\bar{x}_{i,l}$), water uses ($\bar{x}_{i,w}$), own-price supply elasticities ($\bar{\eta}_i$), yield response elasticities to water ($\bar{y}_{iw}$) and rents for scarce resources, land and water ($\overline{\lambda_l}$, $\overline{\lambda_w}$), l stands for land and w stands for water. i stands for the different activities, here crops.

The economic model is written as follows (the regional index is omitted for notational simplicity):

$$\max_{\substack{x_{i,l}\geq 0\\ x_{i,w}\geq 0}} \sum_i \left[p_i \alpha_i \left(\beta_{i,l} x_{i,l}^{\rho_i} + \beta_{i,w} x_{i,w}^{\rho_i} \right)^{\frac{\delta_i}{\rho_i}} - (c_{i,l} + \mu_{i,l}) x_{i,l} - (c_{i,w} + \mu_{i,w}) x_{i,w} \right]$$

$$\text{subject to} \quad \begin{cases} \sum_i x_{i,l} \leq b_l\,[\lambda_l] \\ \sum_i x_{i,w} \leq b_w\,[\lambda_w] \end{cases}$$

with $\rho_i = \frac{\sigma_i - 1}{\sigma_i}$ and $\sigma_i > 0$ the substitution elasticity between land and water and where p_i are output prices, $c_{i,l}$ are variable costs per hectare (excluding irrigation), $c_{i,w}$ are water costs for irrigated crops and b_l and b_w represent regional resource availabilities. $\mu_{i,l}$ and δ_i are parameters that are calibrated.

Crop revenues ($p_i \bar{q}_i$) are calibrated, since the model replicates crop acreage and yields. Calibrating crop-level profits implies that total PMP costs, $(c_{i,l} + \mu_{i,l})\bar{x}_{i,l} + (c_{i,w} + \mu_{i,w})\bar{x}_{i,w}$, must be equal to the observed accounting costs in the reference allocation, $c_{i,l}\bar{x}_{i,l} + c_{i,w}\bar{x}_{i,w}$. The substitution elasticities are set exogenously ($\sigma_i = 0.15$).[15] From the first order conditions we have $\delta_i = \frac{(c_{i,l} + \bar{\lambda}_l)\bar{x}_{i,l} + (c_{i,w} + \bar{\lambda}_w)\bar{x}_{i,w}}{p_i \bar{q}_i}$. The technology parameters $\alpha_i > 0$, $\beta_{i,l} > 0$ and $\beta_{i,w} > 0$ are then calibrated. They are chosen so that at the observed acreage ($x_{i,l}$), (i) the marginal revenue $p_i \alpha_i \delta_i x_{i,l}^{\delta_i - 1}$ equals the per hectare costs $c_{i,l} + \bar{\lambda}_l + c_{i,w} + \bar{\lambda}_w$ and (ii) the crop revenue equals the observed crop revenue $p_i q_i$.

The per cubic meter water cost (c_w) is composed of the water tax and the cost of the energy needed to pump the water. Thus it is a function of the piezometric level of the aquifer (h_n), the remaining parameter are fixed and their values are given in Appendix 2. The linear function is $c_w = tax_{ref} + c_{energy} * \frac{g * l(h_n)}{\eta_{pump}}$ with tax_{ref} the water agency tax, c_{energy} the unit energy cost (electricity here), g the acceleration of gravity, $l(h_n)$ the total head loss, and η_{pump} the efficiency of the pump. With the given parameters the margin dc_w/dh_n

[11] The farmer already has an idea of the order of magnitude of the yearly coefficient before the official announcement because information is available on an Internet site.

[12] The Beauce regions are sufficiently homogenous to consider that modelling a whole region as a unique farmer is acceptable, detailed arguments are given in Graveline and Mérel [34].

[13] This calibration is referred to as the Profit rule in Graveline and Mérel [34]. We choose this calibration because we believe the profit calibration rule to be more likely to be accepted by decision makers as they might be interested in the evolution and replication of profits.

[14] We do not refer to the distribution strategy of water application along the cropping season as we do not have these variables in our model, we only refer to the reduction of water application per hectare and per crop.

[15] Graveline and Mérel [34] argue and test the model's sensitivity to the parameter.

equals −0,98 €/1000 m^3 which means the cost of water increases by about 1 € for 1000 m^3 for every meter decrease in piezometric level. This appears negligible compared to a reference total cost of water of about[16] 59 €/1000 m^3 (or 0,001 compared to a total 0,059 €/m^3 cost).

The calibration parameter and data (cropping patterns, yields, prices) are given in Appendix 2. For more information on the economic model the reader can refer to Graveline and Mérel [34].

In simulation, the economic model runs each year given the available water (b_w, sum of the quotas multiplied by the yearly coefficient) and water costs (c_w) calculated according the piezometric head h_n of the given year. We assume that farmers make their cropping pattern and water application decisions for a relative dry year according Bouarfa et al. [37] who realize a field experimental study on impact of water reduction on farms. This is justified by a risk averse behaviour assumption. The optimised cropping pattern is supposed to be adopted, but the real water application is actualized according to the weather conditions that occur in late spring and summer.

4.2. Hydrogeologic model

The hydrogeological model is a regional semi-distributed model. It follows the principles of groundwater balance (inflow minus outflow) in relation to induced water table changes, using the aquifer storage coefficient. It was set up following three main steps. The first step was to define homogenous hydrogeological zones, the second focused on gathering data and calculating model parameters, while the third concentrated on refining and calibrating the model.

The Beauce agricultural region is divided into four regulatory zones. To provide a satisfactory representation of the hydrogeological processes, we broke the Beauce down into six homogeneous hydrogeological zones. This zoning is based on geological characteristics and on relatively homogenous infiltrations. It is coherent with the regulatory zoning: The Beauce Centrale is further divided into three zones and the three remaining zones are the same as in the regulatory zoning. See Fig. 1.

The hydrogeological model has been refined from the simple groundwater mass-balance equation that states that the piezometric level at the beginning of the growing year, h_{n+1}, is a function of effective natural recharge (R_n), natural drainage (D_n), withdrawal per year ($W_{t,n}$) and per sector t (agriculture, drinking water, industry), storage coefficient (C_{en}) and area (S). The natural drainage is understood as the natural flows to other systems (other aquifer or surface flows). In the case of Beauce, the drainage towards surface river systems is significant. We characterise the drainage in year n as the sum of the drainage of year $n-1$ plus a term that is proportionate to the head difference between two years $h_n - h_{n-1}$. The effective recharge, R_n, is the volume of water from the surface (rain, surface waters) which reaches the aquifer in year n. The Beauce aquifer is characterised by a high level of inertia, as shown by the lag effects of rainfall on groundwater levels and the aquifer's substantial depth. Its size and thickness also explain the system's inertia and long reaction time.[17] Therefore, to improve the model's specification, the recharge should be composed of the infiltration, I_n, directly dependent from the yearly precipitations, and from the previous year's infiltration. Periods of drought, for example, do not reduce groundwater levels suddenly, since the effect is buffered over several years.

We assume that the conductivity within each zone is such that the level of the aquifer on the 1st of April of year n is homogeneous over each zone and represents the sum of extractions of year $n-1$.[18]

Our model is as follows (aquifer regional index is omitted for clarity):

$$h_{n+1} = h_n + \frac{R_n - \sum_t [(1-\beta_t)^* W_{t,n}] - D_n}{S * C_{en}}$$

with

$$\begin{cases} D_n = D_{n-1} + c_d{}^* S * (h_n - h_{n-1}) \\ R_n = (I_n + c_r{}^* I_{n-1})/(1 + c_r) \end{cases}$$

β_t is the return flow from the extraction back to the aquifer. Note the drainage coefficient c_d represents the share of the drainage that is due to the head pressure implied by the difference of the head in year n and year $n-1$. c_r is an inertia term that applies to the recharge of year $n-1$.

The model is calibrated by calibrating the parameters C_{en}, c_d, c_r with observed piezometric and pluviometric data. The calibration of the model is further developed in Appendix 2.

4.3. Characterizing uncertainty: design of scenarios

The future uncertainty is represented by three climatic change and three product price scenarios constructed. All nine combinations of climate change and product price scenarios are performed for the simulations.

[16] Depending on piezometric level, here it is calculated for h = 110 m

[17] See details at http://sigescen.brgm.fr/Fiche-d-identite-nappe-de-Beauce.html.

[18] See Pfeiffer and Lin [47] for a critical discussion on this assumption.

4.3.1. Simulation of future climate scenarios

To characterise uncertainty relative to climatic change, we developed a simplified approach to produce scenarios because the application of downscaling methods was beyond the scope of this research.[19] A series of climatic years are randomly picked from previous years (i.e. 1970–2007) to build a reference climate scenario for the period 2013–2040.[20] A climatic year is characterised by regional infiltration and efficient precipitation. These climatic scenarios are used for the runs and transformed, as described in the next paragraph for climate change scenarios.

To build climate change into the climatic scenarios and account for uncertainty, three climate change coefficients are determined: −0.1, −0.2 and −0.3.[21] We do not account for changes in the distribution of precipitations within the year that could affect some crops more than others. The climate change coefficient is multiplied by the infiltration from 2020 and above. The same coefficient is used to increase the water need per crop ($x_{i,w}$) due to increased evapotranspiration to represent the effect of the rise in temperature. The yield water elasticity, i.e. the impact of water application on yields (see economic model) remains the same because we lacked information on the potential evolution for this parameter. A simple translation of the dose-response function is conducted. These assumptions imply that the yield might be modified as a function of the constraints on water: more water is needed to grow one unit (in quantity). This set of assumptions simplifies the climate change adaptation of the model, particularly, in terms of crop growth with implications for quantities, costs and revenues. However, it enables that we can explore effects on the water balance without resorting to a crop growth model. The economic impact must be interpreted with care.

Thus, these scenarios account for a reduction in infiltration, which affects the groundwater balances simulated using the hydrogeological model and crop water requirements. We assume that the demands for industrial water use and drinking water remain constant on the basis of past and recent trends. The yield data do not account for other climate change effects, such as crop growth, which may be affected by changes in temperature or carbon dioxide concentration.

4.3.2. Uncertainty in product prices and expected product prices

We determined product price scenarios to account for the uncertainty associated with product prices and expected prices (farm product sale prices). The reference scenario is constructed by randomly drawing prices from 1980 to 2014. Price deviations are set at −0.15 and + 0.15 for cereal prices to characterise relative price uncertainty (other crop prices are constant). This coefficient will be applied to product prices in the reference scenario.

5. Results

The different simulations performed are presented in Table 2. Two main types of indicators are considered for the analysis: (i) effectiveness indicators which are for instance the piezometric level or the frequency with the piezometric level respect thresholds and (ii) cost indicators of the policy. The model produces a lot of other output values that could have been analysed (water use, cropping patterns, quantities produced …), but for sake of clarity and to keep the focus on instrument's assessment we stick with these two types of indicators.

5.1. Analysis of the reference instruments

The hydro-economic model was used to simulate the dynamic combined evolution of farming and the aquifer state from 2010 to 2040. To analyse the respective role of both instruments (i) quota and (ii) taxes, shadow values (or marginal benefit) of water were used to indicate the value of +1 or −1 m^3 of water. The shadow value indicates if the quota or the tax is constraining as demonstrated in section 2.2.2. According to our results, the quota is constraining most of the time in most of the regions. This is coherent with the fact that the quota system is a local policy that was designed and adapted for the region, unlike the tax, which is national and not specifically geared to incentivising Beauce farmers. This also illustrates that the two instruments complement each other, because they are both active. The shadow values indicate that the areas where water is valued most (i.e. with high shadow values) are Montargois and Fusain, in the east of the region. Here, substitution resources are being considered by the administration and farmers to compensate for water restrictions with a low coefficient (often around 0.5, reducing the quota to only 50% of its base level).

5.2. Impact of climatic change with the reference instrument

We then explore the impact of increasing water scarcity due to climate change on the current hydro-economic system using the reference instrument and considering price uncertainty. Current management fails to compensate for climate change, as shown by the

[19] Boé et al. [48] details the various methods available to produce climatic scenarios and propose an application to French river basins.

[20] A first test was realized to see if the distribution of previous years was statistically similar to a normal law or other common probability laws, but this was not the case. This would have enabled to produce more consistent future climate scenarios that would not replicate exactly the distribution of previous years and that could have been modified on their standard deviation also. A longer time period would have probably enabled to fit a probability law.

[21] Boé et al. [48] give a decrease of about −3% for spring and −10% for summer precipitation in the Loire river basin and +19% evapotranspiration in spring and −13% in summer for the period 2046–2065 - both parameter intervene in the infiltration determination. Similar patterns are provided for the Seine river basin. Ducharne et al. [45] estimate for a pessimistic A2 SRES scenario a −23% reduction in precipitation of the Seine river basin and −37% in the groundwater recharge at the 2100 horizon.

Table 2
Simulation set performed.

	1	2	3
Instruments	Ref	Ref	All
Climate scenarios	3 climate scenarios (no climate change)	3 climate change scenarios	
Price scenarios	3 price set scenarios		

Table 3
Shadow values of water with the reference instrument: flexible quota & tax for each region and over the years 2010–2040 - No climatic change, no uncertainty in prices.

	Mean shadow value €/m^3	Distribution of cases	
		case B: cost constraining	case A: quota constraining
		$\lambda_{water} = 0$	$\lambda_{water} > 0$
B. blesoise	0,04	30%	70%
B.c.calc	0,07	3%	97%
B.c.sable	0,03	33%	67%
B.c.sous couv.	0,15	3%	97%
Fusain	0,27	3%	97%
Montargois	0,38	0%	100%

distribution of the frequency of threshold compliance (the frequency of years when the piezometric level is above the 3 different thresholds, considering all simulations of climate, prices and years between 2014 and 2040). This is lower for the simulations with climate change than for the reference for all the regions (see Fig. 3). The instruments' autoregulation capacity seems insufficient to maintain piezometric levels and threshold levels are reached more often with climate change. However, the effect of climate change does not dramatically change the patterns of threshold level frequencies. The results suggest two different patterns of regional sensitivity in terms of the agriculture-aquifer system's response to climate change. B. Blesoise, B. c. calc., B. c. sable and B. c. ss couv. are significantly affected by climate change because the water levels reach the highest threshold with about 20% less frequency. In contrast, Montargois and Fusain are little affected by climate change, as shown here. However, their threshold levels are not fully respected, even without climate change.

When it comes to conserving the piezometric levels with climate change in all regions, the effectiveness of the reference

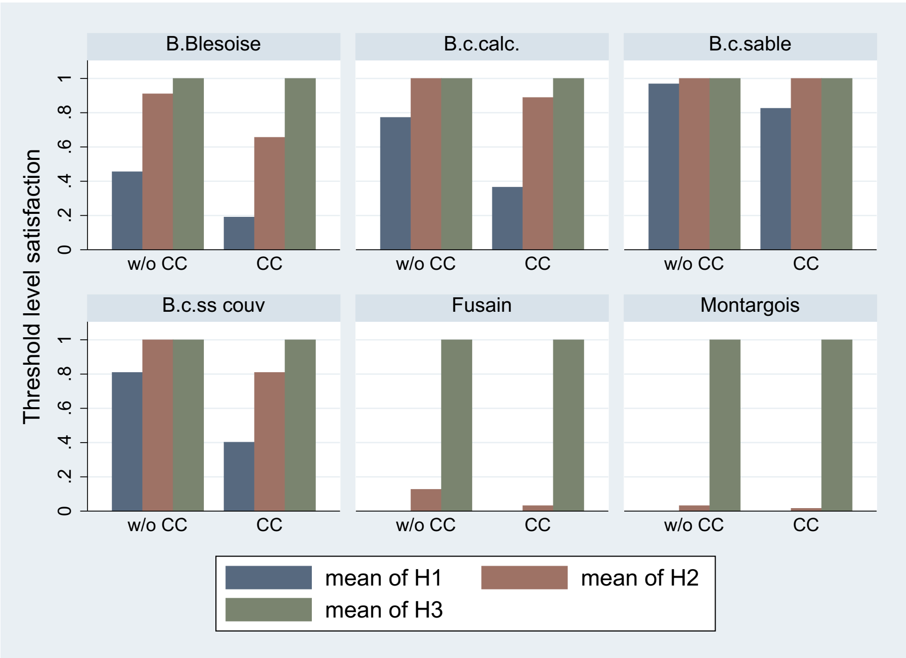

Fig. 3. Frequency of piezometric threshold levels respect between 2020 and 2040 with and without climate change. "w/o' stands for without climate change, "CC" stands for climate change simulations.

Table 4
Cost for farming, social cost, effectiveness and cost-effectiveness and shadow value of water of alternative instruments (*relative piezometric level increase compared to no irrigation) (*Cost: Profit loss compared to no regulation; ** Social cost (net of taxes/subsidies); Effectiveness = $(H - H_{NoReg})/(H_{NoIrr} - H_{NoReg})$. St.D.: standard deviation.

		Ref	6 reg	6 reg +	Tax	FlxTax	FlxTxQ	Substi	Buybck	Desirr
Cost for farm. (* €/ha)	Mean St.D.	41,3	41,9	52,6	33,4	84,0	85,8	39,8	37,4	33,4
		25,3	26,1	30,6	13,6	24,5	27,6	23,4	25,8	28,3
Social cost (** €/ha)	Mean St.D.	35,5	36,1	47,8	19,3	31,4	38,1	33,8	41,1	43,8
		25,8	26,7	31,0	13,4	24,6	28,4	23,8	32,1	31,0
Effectiv. (Relative on 1)	Mean St.D.	0,55	0,55	0,62	0,45	0,58	0,61	0,55	0,59	0,59
		0,12	0,12	0,11	0,10	0,08	0,08	0,12	0,11	0,09
Cost-Effec. (€/ha/eff. unit)	Mean St.D.	65,5	66,3	78,1	43,7	53,8	62,2	62,7	68,1	73,7
		8,9	8,9	9,5	8,6	4,0	6,6	8,3	8,8	8,3
Shadow value of water (€/m^3)	Mean St.D	0,118	0117	0,158	0056	0,008	0033	0,107	0088	0,066
		0,054	0054	0,063	0031	0,012	0027	0,050	0055	0,050

instrument seems limited; in Montargois and Fusain the instrument is already ineffective in the reference situation (without climatic change).

The average cost for farming due to reduced water availability resulting from climate change is limited to −3% of annual net revenues after 2020 (years with effect of climate change). Even though the effects on individual farms should be investigated and would reveal differences, the cost induced by climate change on farming seems limited in Beauce. This can be explained by the fact that irrigated agriculture adapts and the effect on water resources is limited, more specifically (i) the total cultivated area remains stable, (ii) the greater water requirements for growing crops are satisfied by increasing water use per unit of land and decreasing the area with irrigated crops (extensive margin adjustment). Our model does not account for the specific effects of temperature on crop growth. Therefore, these conclusions must be interpreted with care.

These results, both the deterioration of piezometric heads and the low cost for farming may be an incentive to revise the actual policy in the light of climate change.

5.3. Cost-effectiveness of alternative instruments under climate change scenario

This paragraph presents and discusses the simulation results of different economic and regulatory instruments presented in section 2.2.3. They are tested for the climatic change scenarios and price uncertainty scenarios.

Results for both types of indicators are presented in Table 4. Cost for farming is the profit difference between the policy and an open access scenario (no regulation). Social cost is the cost for farming net of water tax revenues or water subsidy expenses. The effectiveness is an indicator on a scale of 1 regarding the relative closeness of the piezometric level (h_n) compared to the worst case (open access) and the best base scenario (no irrigation). Effectiveness is calculated as $E = (H - H_{NoReg})/(H_{NoIrr} - H_{NoReg})$. An effectiveness of 1 (or 100%) means piezometric level are not affected by farming, an effectiveness of 0 means there are as affected as in the open access case. Cost-effectiveness is the ratio of the social cost by the effectiveness in €/ha/eff. unit, the lower the better; it could also be called the efficiency. The shadow value of water is given to indicate the level of constraint provided by the quota system.

The different instruments do not provide very contrasted results in terms of piezometric level (or effectiveness). More differences are observed in terms of cost for farming as well as for social costs. As expected, there is a relative trade-off between piezometric head and agricultural profits: when costs for farming increase, the piezometric level increase. The challenge is to identify and design an instrument with the best trade-off, e.g. the lowest cost-effectiveness ratio for a given level of environmental performance. In theory economic instruments provide better cost-effectiveness because they encourage those water savings with the least costs. However, the overall water savings (e.g. the environmental performance of the instrument) are not guaranteed or fixed ex-ante.

6 reg + and *FlxTxQ* are most effective (resp. $E = 0{,}62$ and $E = 0{,}61$) but *FlxTxQ* is more cost-effective than *6 reg +* (62,2 < 78,1). Right after are *FlxTax, Buybck* and *Desirr* instruments ($E = 0{,}58$ and 0,59) and *Flxtax* is more cost-effective than *Buybck* and *Desirr* instrument (53,8 < 68,1 < 73,7). *Buybck* is more cost-effective than *Desirr* which is explained because *Buybck* allows farmer to adapt the water application rate per hectare (intensive margin), rather than suppress irrigation altogether (extensive margin). Both instruments are appealing in comparison to the reference instrument. They generate lower costs for farming and improve environmental performance, provided public money is spent (social cost is higher). On average, *Desirr* reduces water use by 5% and *Buybck* by 4% compared to the reference instrument.

The *Tax* instrument (no quota) is less effective at maintaining piezometric levels (0.45 versus 0.55) than the reference. Therefore, it is not a candidate for improving water management.

The *Substi* instrument allows farmers to substitute some of their groundwater withdrawals for irrigation with water collected in ponds in the autumn and winter. The simulation suggests that water is collected and used for irrigation to substitute groundwater in all regions except in B. c. sable. Depending on the year, the pond water substitutes or supplements groundwater use to increase overall water use. On average, this option increases use (supplementary use) by 5%. However, from an environmental point of view, the *Substi* instrument is of little interest because it is less effective than the reference instrument. Nonetheless, it is slightly cheaper for farming and society (−2 €/ha), which explains why farmers are willing to implement this type of solution.

The *6 reg* instrument, which consists of introducing a differentiation in the calculation for the coefficient between the three

Table 5
Effectiveness and cost-effectiveness in each region for all instruments.

Region	Ref	6 reg	6 reg +	Tax	FlxTax	FlxTxQ	Substi	Buybck	Desirr
Effectiveness									
B. blesoise	0,42	0,42	0,51	0,28	0,57	0,58	0,42	0,46	0,49
B.c.calc.	0,43	0,43	0,52	0,34	0,47	0,49	0,43	0,47	0,47
B.c.sable	0,25	0,18	0,32	0,18	0,38	0,38	0,25	0,28	0,35
B.c.ss couv.	0,81	0,83	0,86	0,79	0,82	0,85	0,81	0,85	0,85
Fusain	0,86	0,86	0,89	0,67	0,83	0,89	0,84	0,89	0,88
Montargois	0,90	0,90	0,92	0,64	0,71	0,91	0,87	0,91	0,91
Cost-effectiveness									
B. blesoise	26,2	26,2	33,0	9,1	19,2	21,0	25,9	23,1	34,5
B.c.calc.	76,2	76,2	98,0	50,4	48,8	54,0	76,1	67,8	77,7
B.c.sable	8,3	6,9	9,3	6,2	6,4	6,4	8,3	8,9	8,7
B.c.ss couv.	100,5	113,1	126,6	80,6	71,6	92,9	100,5	102,4	107,3
Fusain	125,8	125,8	131,7	63,3	106,7	123,1	109,7	100,4	104,5
Montargois	166,8	166,8	167,2	111,1	158,1	167,8	146,1	147,9	152,1

regions B. c.calc., B. c. sable and B. c. ss couv, only seems effective at maintaining better piezometric levels for B. c.ss. couv. It has no impact on the largest region (B.c. calc.) and has a negative impact (reduction of water availability constraints) on B. c. sable. Thus, it seems irrelevant, given that it has negligible aggregated impact on effectiveness and shows a positive cost, compared to the reference instrument.

The results of the mean and standard deviation of the shadow value of water for each of the policies indicate the most active mechanisms (quota or tax), as discussed previously. This can be interpreted as the cost of the water resource constraint (quota constraint). All alternative instruments, except the *6reg +* , show a reduced shadow value of water. This indicates a lower constraint in terms of the quota system and a relatively high price-based incentive. Notably, the *FlxTxQ* instrument presents a shadow value of water of 0,033 €/m^3, which is far below the reference cost of the water use constraint 0,117 €/m^3.

5.4. Regional results

Table 5 gives the effectiveness and the cost-effectiveness of instruments for each region. Two types of regions can be distinguished: in relative terms the three first regions (B. Blesoise, B. c. calc., B. c. sable) have a higher potential for improvement and a lower cost-effectiveness than the three other regions (B. c. ss. couv, Fusain, Montargois). These patterns are similar accross instruments. A positive relationship between cost-effectiveness and effectiveness is consistent with intuition and corresponds to increasing marginal cost of environmental efforts. However, it is interesting to note that in some cases, for instance *FlxTax*, good effectiveness can also be characterised by relatively low cost-effectiveness, which is particularly interesting.

When comparing the effectiveness of alternative instruments with the reference instrument, the evolution is similar for all regions (positive or negative), except for the *FlxTax* instrument. The latter improves the piezometric levels for the first four regions and reduces it for Fusain and Montargois. This shows that in Fusain and Montargois, the quota system is necessary to maintain the same effectiveness as in the reference. In the other regions, a nearly pure price-based instrument (the *FlxTax*) improves both the effectiveness and the cost-effectiveness compared to the reference instrument. The *FlxTxQ* seems a better choice because it improves the effectiveness in all regions, albeit at a higher cost.

The substitution instrument shows that the agricultural response differs according to the region: although water use increases by only 5% globally, it increases by more than 80% in Fusain (where the option is also the most controversial). In the B. c.sable, this option is not adopted because substitution does not cost less than groundwater or the shadow value of water for irrigation, i.e. the opportunity cost of extra water use.

5.5. Robustness

The concept of robustness offers a different perspective that considers the dimension of uncertainty or any source of variability, i.e. space, time (years), price and climate scenarios (which integrate climate change assumptions). These aspects are ignored in a deterministic setting, which aggregates different results into a mean (as presented in previous sections). Robustness is particularly relevant for the environmental indicator (piezometric level) because groundwater flows into surface watercourses. The cause and effect is discontinuous, for example, below a certain groundwater level there is a very strong impact. With regard to the impacts on farming costs, robustness could also be useful in terms of agricultural sustainability (one dry season can put a farmer out of business, although this is not the case in Beauce). Table 6 presents the selected instruments with the robustness MinMaxRegret algorithm according effectiveness and cost-effectiveness. Optimality results from the previous section are reported for comparision. To produce unique combined criteria, we combine the ranking for both indicators.

For effectiveness, the results show that the *FlxTxQ* is more robust than the *6 reg +* instrument, while *6 reg +* is more optimal than

Table 6
Ranking the instrument according optimality or robustness criteria for the two indicators (i) effectiveness and (ii) cost-effectiveness and for a combined robustness of these two indicators.

Rank	Effectiveness		Cost-effectiveness		Combined ranking	
	Optimum	Robustness	Optimum	Robustness	Optimum	Robustness
1	6 reg +	FlxTxQ	Tax	Tax	FlxTxQ	FlxTxQ
2	FlxTxQ	Desirri	FlxTax	FlxTax	FlxTax	FlxTax
3	Desirri	FlxTax	FlxTxQ	FlxTxQ	6 reg + /Tax	Tax
4	Buyback	Buyback	Substi	Substi		Desirri
5	FlxTax	Tax	Ref	Ref	BuyBck/Desirri	Buybck
6	6 reg	6 reg +	6 reg	6 reg		6reg/Substi
7	Ref	6 reg	Buybck	Desirri	Ref/6 reg/Substi	
8	Substi	Ref/Substi	Desirri	Buybck		Ref
9	Tax		6 reg +	6 reg +		6 reg +

FlxTxQ (E = 0,62 vs. 0,61). This result indicates that *6 reg* + generates lower piezometric levels than *FlxTxQ*, although it produces slightly better outcomes on average. The *reg 6* + seems not to be robust in terms of effectiveness. Therefore, we can discard this option, despite the fact that it appeared optimal. The *Tax* instrument is the most cost-effective considering both optimality and robustness. The combination of both indicators provides similar results for the first best: the *FlxTxQ* is preferred with both criteria. Considering robustness has little effect on the results of cost-effectiveness.

However, robustness might be achieved at a higher cost than optimality. Here, adopting the *FlxTxQ* instrument versus the *6 reg* + instrument induces benefits in terms of social costs (tax revenues mask the extra farming costs: 10 €/ha) while farming cost increase by 33 €/ha (see Table 3).

When spatial variability (differences between regions[22]) is considered in the robustness analysis, the results remain the same.

6. Conclusion

The main local instrument in Beauce, which is a flexible quota system, is highly original. As far as we know, it is unique. It has the advantage of introducing flexibility in an instrument with a rigid design. It is coupled with an economic instrument, a low tax on water use which is not a local policy instrument but a european water policy instrument. Although the incentive is very modest, it is sometimes acting on behaviour. The flexibility limits the cost for farming, while ensuring that certain environmental objectives are achieved. Interestingly, the flexible quota system addresses the problem of the over-allocation of water entitlements. Instead of reducing water rights definitively, the rights are revised each year depending on the level of the aquifer. Under French law, water entitlements are not rights but annual authorisations that are systematically renewed each year. However, the difficulty of reducing historical reference authorizations is particularly critical. The recent change to a "single collective management body", which will be in charge of controlling the total annual volumes for abstraction in a region, illustrates another strategy. The aim is to avoid a top-down decision (imposed by the administration on the farmer) to reduce individual water abstraction volumes. In this system, the single management body (which is not governmental) will monitor compliance with the total water allocation, by managing individual water allocation. However, this reference instrument does not seem to be sufficiently effective to achieve good environmental performance. This statement is particularly pertinent in the light of climate change forecasts, given the likely reduction in rainfall and recharge, as well as the increase in evapotranspiration.

The simulations described in this paper show that increasing the economic incentives, with a flexible tax on water use (that varies with the state of the groundwater), seems both effective and cost-effective. It also appears to be robust in a context of climate and price uncertainties (*FlxTxQ*, which maintains the reference flexible quota system). The combination of both quantitative-based and price-based instruments seems particularly pertinent in Beauce, where the state of the aquifer allows for the withdrawal of different volumes of water, depending on the years. The quota ensures a minimum fixed constraint that is independent from the water demand variation (linked to price variations). The tax introduces flexibility, by cutting the demand for farms where the marginal net benefit of water use is less than the tax (this varies with price). Acceptability may also be higher than with a single instrument that would imply a more constraining quota or tax. In addition, the robust flexible quota and tax policy could easily be implemented because of the existing sophisticated administrative framework for adapting and enforcing annual quotas and tax levies (tax payment procedures, information on annual coefficient, etc.). With the shift towards a regional quota (rather than an individual quota), the increase in use of price-based instruments, such as the flexible tax, could help identify and allocate cheaper water savings. It is an alternative to negotiations that aim to reallocate the regional quota to individuals with very high transaction costs.

Introducing flexibility in terms of the volume of water allocated (quantitative) or the tax level is a cost-effective feature in basins where the intra-annual variability of available resources is significant. It is a way to reduce the cost that differs from a fixed tax or quota. It should also satisfy water resource constraints in dry years. This new system based on two instrument could be justified (in

[22] The spatial robustness enables to select instruments that do not induce extreme negative outcomes in one region compared to the best region and thus induce relative homogeneous outcomes among regions.

the Tinbergen rule logic of one instrument per policy objective) by (i) authorizing total yearly water use according the amount that can be sustainably handled by water resources (quota constraint) and (ii) reallocating water use where water is most valued to maximize social benefits in time. In terms of sequencing the introduction of instruments in time, it might be smarter to first reinforce the quota (which is by far more constraining today than the tax) and then to introduce the flexible tax to reallocate extra water savings. Although our modelling results are obviously case specific, the analysis of the mechanisms discussed in this paper has broader application that we develop in the two following paragraphs.

The two instruments we analyse for the reference policy have been designed for (i) safeguarding piezometric levels (quota instrument) and (ii) contributing financially for a potential harm to the environment (tax) while acting as an incentive to limit water use. We show that the tax is rarely active as an incentive (Table 3) (no change in behaviour is observed) and can question the interest of the current european WFD withdrawal water tax because it is not locally adapted and have little chance to act as an incentive. As such it could be smarter to present it only as an individual contribution to a collective financial effort to manage water bodies rather than arguing that it acts as an incentive without having tested the efficiency (depending on marginal water value which is very variable throughout Europe's farming systems) or to upgrade it's design in order to guarantee its incentive characteristic.

Even though our results show little effect of the reference tax on the water use (and environmental performance), they show that the most robust policy among the options considered is a combination of a flexible tax and a flexible quota. The flexible tax has been redesigned from the initial tax to be constraining and reflect the need for water savings according the state of the water bodies. This result encourages the adaptation of economic instruments to the regional hydrological and economic specificities in Europe. If the tax should have an incentive role of reallocation (induce less use where water is less valuable and reallocate it when or where it's more valuable) the tax should be properly and locally adapted according economic specificities to be effective.

From a methodological point of view, the hydro-economic model we developed is an interesting approach for exploring a variety of management alternatives and policies relating to the hydrogeological and agricultural economic system. The proposed approach is particularly relevant because it suits all types of policy exercises and provides detailed insights into agricultural economics: shadow values of water make it possible to interpret the agricultural response in terms of alternative water resources. Our model is a good trade-off between detailed modelling and calibration, on the one hand, and implementation and data requirements, on the other hand. The perfectly calibrated econom ic model produces detailed adaptation margins, including deficit irrigation (adjusting the water application rate). However, modelling on a regional scale does not take account of individual specificities or analysis. For instance, the problem of “dead volumes” (over-allocation) cannot be analysed at farm scale with our model. The simplified hydrogeological approach is satisfactory from a calibration point of view because it replicates the observed years correctly. The main advantage is that it provides a unique platform to accommodate a variety of simulations. In addition, it is calibrated accurately to represent realistic hydrogeological and economic processes. A robustness criterion is used to account for (and avoid) unsatisfactory outcomes in the face of uncertainty. The criterion is developed for three dimensions: time and space variability (regional) and climate uncertainty. Robustness affects the results, which suggests that it should be taken into account in future modelling.

The perspective of this work includes an improved representation of other (non-agricultural) water requirements, including ecological water demands and their benefits. Further analysis could focus on integrating uncertainty with regard to the evolution of agricultural policy and input prices. This would be helpful for the development of adapted and robust or flexible policy changes.

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Appendix 1. Crisis Management in Beauce

Since 1995, the first quantitative groundwater management instrument to be applied in Beauce involved temporary water use restrictions in summer, when surface river flows were below threshold levels. When the first aquifer threshold level is reached (“alert”), farmers must stop irrigating for 24 h or 48 h per week. When a second threshold is reached (“crisis”), all non-essential water uses, including agricultural irrigation, must stop. These constraints apply to all farmers in Beauce.

The crisis management measures act as a safety net. If the planning policy has failed to avoid a crisis situation, extra measures are taken to reduce the impact of the drought on ecosystems and priority uses. The more restrictive the planning policy is, the more costly it is for farming and the more efficient from an environmental protection point of view. The restriction is imposed with no warning, per se, when there is no rain and when crops and rivers need water. The economic impacts of restrictions can be seen as the damage cost of drought. They necessarily cost more for the farmers than adapting cropping and irrigation in advance. The farmer's capacity to adapt is limited once crops have been sown (sunk costs). On the other hand, greater caution and stronger restrictions (reducing the quota or increasing tax) represent a high cost for farmers and the environmental benefits are limited. Greater restrictions involve negotiations with the farming sector and high transaction costs, which should also be considered.

According to experts, a 24- or 48-h irrigation ban on abstraction has a limited impact on the aquifer. Most farmers find ways to

organise irrigation and labour at least cost to continue supplying the same quantity of water to their crops. However, discrepancies emerged with regard to the impact of the restriction, which call for a detailed field analysis that is beyond the scope of this paper. The temporary restriction measures in Beauce are less restrictive than elsewhere: the "alert" level imposes a 50% reduction on abstraction for non-essential uses. The temporary restriction also imposes restrictions on other users. Restrictions are imposed on citizens for non-essential water uses, such as watering gardens, filling pools or cleaning cars. The alert level simply bans water use for several hours per day. Therefore, the impacts are negligible because it is easy to postpone water use until later the same day (e.g. watering the garden, etc.), even if it causes some inconvenience.

Appendix 2. Data and calibration

The economic and hydrogeological models were calibrated for the six regions.

Hydrogeological model calibration

The calibration phase aims to calibrate the following model parameters: storage coefficient C_{en}, the drainage coefficient c_d and the recharge coefficient c_r. It also serves to initialize the drainage value (D_0).

The hydrogeological calibration programme consists in minimizing the distance between each year and each zones' estimated piezometric level h_n as specified in our model and the observed piezometric level using non-linear least squares. The program is solved in GAMS with a non-linear solver.

The calibration performs well as the observed and modeled piezometric levels for all regions are close, except for region *Montargois* (see Appendix 3 for the graphs that compares observed and modeled years). The Nash-Sutcliff index [38] is 0.931, 0.977, 0.981, 0.965, 0.939, 0.675 respectively for the 6 regions and 0.951 for the whole model. A perfect fitted calibration would give an index of 1.

Data for hydrogeological model calibration

Piezometric heads, withdrawals and recharge are observed for the calibration period 1997 to 2009 at a yearly time step.

- **Piezometric heads**. - Piezometric heads. Groundwater monitoring data for the reference piezometers of each of the hydrogeological sectors are collected from the national database for groundwater (ADES, www.ades.eaufrance.fr). We assume that the piezometric heads of the reference piezometers are representative of each zone. They have been chosen as "reference piezometers" by the administration to monitor the state of the groundwater and impose groundwater abstraction restrictions to the corresponding areas, as a function of the piezometric head [39].

- **Withdrawals**. A water withdrawal database has been set up from data produced by water agencies on the basis of the taxes recovered for water uses for the years 1998–2009. Thus, we were able to compile water withdrawal per type of user (water utilities for drinking water distribution, industries and farming), per area, per type of resource and per year. It should be possible to generate a good approximation of the total volume of water abstracted from the aquifer, since farmers have to declare their withdrawals and pay the corresponding tax. However, there is a minimum volume (7000 m^3) below which farmers do not have to declare their water use.[23] We assume that most withdrawals are declared for the tax and recorded in the database. In order to correct the data, we added 10% of the volume of the observed agricultural use to account for missing data. For water utilities and industry, we assume that all volumes are declared.

- **Infiltration**. Infiltration is calculated for each year and aquifer zone. The limestone aquifer is characterised by high infiltration rates, while sandstones and clays show more surface runoff. The infiltration (or recharge) is calculated from two values: the effective rainfall and a geomorphological index (IDPR). Effective rainfall is the rainfall that is available for runoff or infiltration. It is calculated from meteorological data (MétéoFrance) available at a grid size of 8 km × 8 km. The index (IDPR) represents the characteristic of a soil with respect to infiltration and runoff. The estimation of this index is detailed in Schomburgk et al. [40].

The return flow $beta_t$ are set to zero in the case of the Beauce aquifer because no return flows to groundwater from irrigation or sewage are considered significant. The fact that irrigation water is largely used by crops (sprinkler technology has a good water use effectiveness, close to 80%) and the geological formation of the aquifer support this assumption.

Economic model calibration

The model is calibrated on observed cropping patterns for 2009 taken as the reference situation (see tables below). Sources of data are the French farm payment agency for cropping patterns and Ministère de l'agriculture et de l'agroalimentaire [41] for crop yields and land rents. We use reference irrigation levels conditional on soil type from Morardet and Hanot [36] and update them using more recent information by Bouarfa et al. [37].

Expected prices of outputs for the year 2009 are calculated based on adaptive expectations from observed prices for the years 2005–2008 [42]. Yearly average prices are obtained from the French statistical office, costs are recovered from Brunel, Bouarfa, and Ruelle [43] and yield response to water are characterised with Morardet and Hanot [36].

[23] Note that this volume correspond to less than about 4 ha of irrigated corn, or about 10 ha of irrigated wheat.

2009 correspond to relative important reductions of water availability compared to the initial quantity of quotas, as the coefficient was 0.59 in 2009. The climate of 2009 had a wet spring but a dry summer. However, likely evolution might strengthen these constraints with a coefficient up to 0.2 [37]. The interest of having an already constraining reference but not an extreme one is that the simulations keep the model within a reasonable range that guaranty model validity.

The total agricultural area modeled is 593 000 ha, which is more than 90% of the total farming area. The remaining 10% include mainly set-aside, pasture and orchards. Within the modeled area about 20% are irrigated crops in the reference situation.

Table 7
Cropping patterns and prices in the reference situation used for calibration

Crop	Total (ha)	Cropping patterns (ha)						Prices €/ha
		B. Blesoise	B.c. calcaire	B.c. sable	B.c. couv.	Fusain	Montargois	
Wheat	164 662	17 308	91 603	24 987	10 884	10 167	9713	11,5
Irr. wheat	28 571	3367	21 447	359	773	844	1781	11,5
Corn	3521	68	144	400	588	50	2271	11,9
Irr. corn	39 938	3366	25 801	679	3990	1160	4943	11,9
Winter barley	47 623	3558	29 665	5433	2214	4196	2558	11,8
Irr. winter barley	18 022	2315	13 473	99	338	1060	737	11,8
Spring barley	40 718	155	19 825	8206	3210	5771	3551	12,1
Irr. spring barley	18 028	2009	12 489	172	564	1705	1091	12,1
Durum wheat	64 044	15 169	39 961	1853	3626	1905	1530	11,6
Irr. Durum wheat	24 564	4222	19 228	65	341	482	226	11,6
Rape seed	65 393	12 271	37 758	9128	3284	1749	1204	15,6
Sunflower	8374	2900	2230	438	564	1005	1238	18,1
Pulses	2917	58	397	2399	4	25	36	11,5
Irr. pulses	9717	1126	7718	308	106	333	125	11,5
Rape seed (biofuels)	4101	289	3250	272	68	169	53	13,6
Sugar beet	13 010	7	5003	4194	887	2040	880	2,3
Irr. Sugar beet	21 192	79	16 569	561	576	2798	609	2,3
Potato-Veg	1309	64	633	331	103	35	142	11,4
Irr. Potato-Veg	17 677	1080	14 897	467	751	411	71	11,4
Total	593 383	69 412	362 090	60 351	32 869	35 904	32 758	–

Table 8
Yields in the reference situation used for calibration (100 kg/ha)

Yields (100 kg/ha)	B. Blesoise	B.c. calcaire	B.c. sable	B.c. couv.	Fusain	Montargois
Wheat	73.4	80.0	84.4	73.4	75.9	73.4
Irr. wheat	78.2	85.2	89.9	78.2	80.9	78.2
Corn	75.0	74.6	84.6	62.0	65.9	62.0
Irr. corn	108.0	109.5	102.1	110.0	108.6	110.0
Winter barley	66.4	72.5	76.2	64.4	66.6	64.4
Irr. winter barley	75.0	79.8	83.7	70.7	73.1	70.7
Spring barley	71.8	72.8	73.4	70.8	71.4	70.8
Irr. spring barley	77.1	78.2	78.8	76.0	76.7	76.0
Durum wheat	66.2	71.9	73.8	71.0	71.5	71.0
Irr. Durum wheat	70.3	76.2	78.4	75.3	75.8	75.3
Rape seed	39.0	41.1	41.9	37.0	37.9	37.0
Sunflower	25.0	30.6	33.9	30.0	30.7	30.0
Pulses	49.4	48.0	52.4	46.5	47.3	46.5
Irr. pulses	53.0	51.5	56.2	49.9	50.8	49.9
Rape seed (biofuels)	39.0	40.9	41.9	37.0	37.9	37.0
Sugar beet	929.5	934.3	900.2	929.5	924.4	929.5
Irr. Sugar beet	932.1	936.9	902.6	932.1	927.0	932.1
Potato-Veg	459.3	434.2	437.1	446.7	449.1	446.7
Irr. Potato-Veg	568.8	552.1	488.7	536.1	531.2	536.1

Table 9
Net revenues in €/ha in the reference situation

Crops	B. Blesoise	B.c. calcaire	B.c. sable	B.c. couv.	Fusain	Montargois
Wheat	776	871	935	776	812	776
Irr. wheat	785	894	961	793	816	802
Corn	480	475	599	317	366	317
Irr. corn	579	614	520	623	551	653
Winter barley	640	725	777	613	643	613
Irr. winter barley	686	763	816	639	654	648
Spring barley	1021	1038	1049	1003	1014	1003
Irr. spring barley	1044	1076	1084	1039	1031	1050
Durum wheat	1035	1155	1197	1137	1147	1137
Irr. Durum wheat	1037	1174	1219	1156	1142	1169
Rape seed	655	708	728	604	626	604
Sunflower	501	651	740	635	653	635
Pulses	668	645	717	621	635	621
Irr. pulses	675	655	733	630	626	641
Rape seed (biofuels)	548	591	612	504	522	504
Sugar beet	918	927	862	918	908	918
Irr. Sugar beet	723	752	682	746	686	773
Potato-Veg	2403	2185	2209	2293	2314	2293
Irr. Potato-Veg	3111	2982	2428	2845	2749	2873

Parameter values

In the application following values are taken for the cost calculation of water:

$$c_{energy} = 0.07\ €/\text{kwh}$$

$$\eta_{pump} = 0.70$$

$$r_{ae} = 0.014\ €/\text{m}^3$$

$$\text{Total head loss } l(h_n) = 150 - h(n) + 6$$

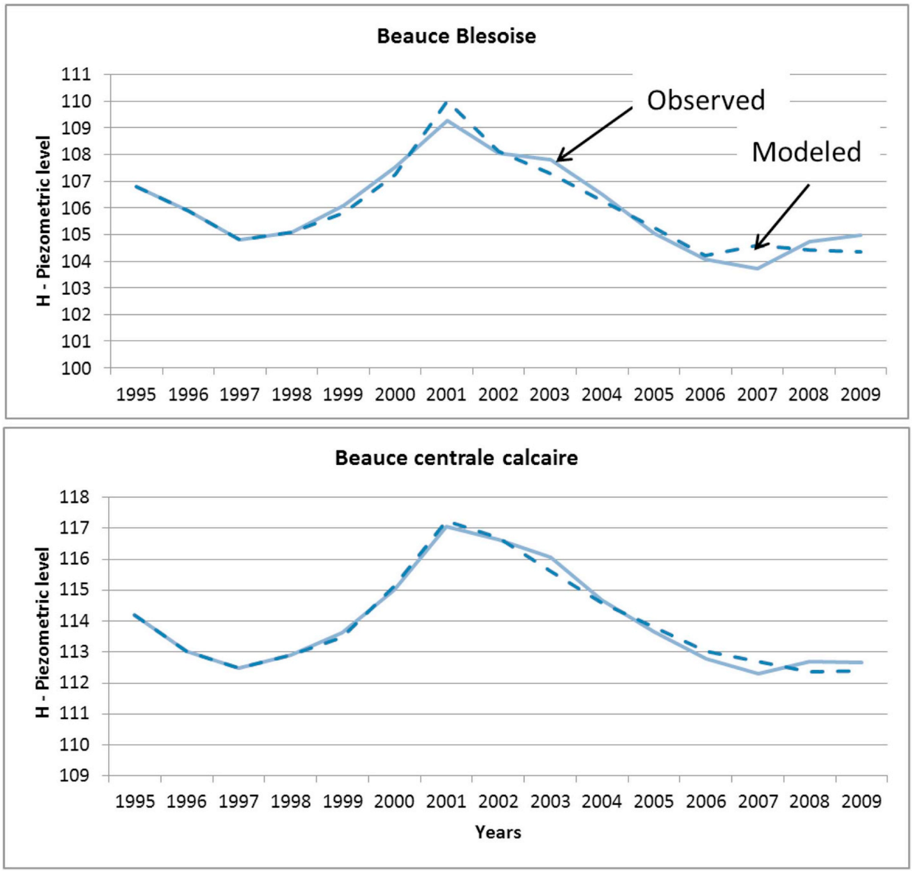
$150m$ being the soil level above sea level and $h(n)$ the height of the aquifer. 6 is the estimated head loss in the pumping configuration.

The following table gives the parameter values for the hydrogeological model.

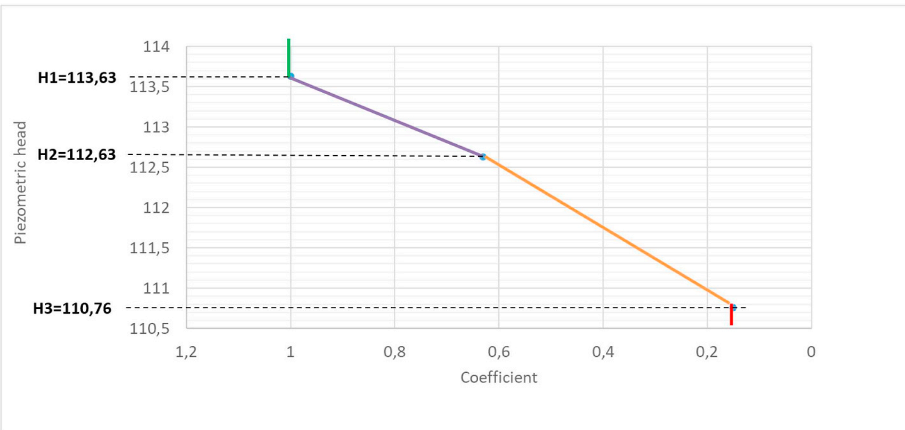
Table 10
Parameter values for the hydrogeological model. c_{en} is the storage coefficient, c_d the drainage coefficient, c_r the recharge coefficient, representing the inertia of the system. Area in km^2

	B. Bles.	B. c. calc.	B. c. Sables	B. ss couv.	Fusain	Montargois
Area	982	4616	1684	1224	469	777
	0.048	0.068	0.057	0.027	0.061	0.120
	0.228	0.321	0.283	0.142	0.410	0.551
	0.258	0.650	0.721	0.577	0.325	0.000

Appendix 3. Comparision between observed and modeled piezometric levels for Beauce Blesoise and Beauce centrale Calcaire



Appendix 4. Characterization of the coefficient: An example of the relationship between piezometric head and coefficient for the Beauce centrale (largest region)



Regulatory calculation of the yearly coefficient according to piezometric head (in meter) since 2010 for the Beauce centrale. Source: Own elaboration with DREAL Centre data.

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